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PLASMA FLOW PAST A TWO-DIMENSIONAL MAGNETIC DIPOLE

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SUMMARY

The interaction is investigated of supersonic plasma flow with a dipole magnetic field. The results of measurements are in agreement with the assumption of collisionless shock wave formation.

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A spherically shaped tarella [1] is most frequently used in simulating the interaction between the solar wind and the Earth's magnetic field. The use of contactless diagnostic methods does not provide the possibility of determining the plasma parameters directly at a given point, for the complex configuration of the magnetic field makes it possible to obtain only the parameter values averaged along the region of their strong inhomogeneity. The use of contact methods, for instance, of Langmuir probes, is inadvisable because of their considerable disturbing effect on plasma flow, as well as on account of difficulties arising in the processing of probe measurements in an intense and inhomogeneous magnetic field.

The aforementioned difficulties disappear when use is made of a two-dimensional dipole formed by two parallel conductors with currents flowing in opposite directions. The magnetic field intensity of such a two-dimensional dipole is a function of coordinates r and ϕ only, and is independent of the coordinate z. Therefore, probing with electromagnetic radiation or particle beams directed along rods with current makes possible the obtaining of the spatial distribution of concentration and temperature. The values of parameters along the path of the beams can vary only at the expense of the initial spatial inhomogeneity of plasma flow. Applying an adequately collimated probing beam and selecting a sufficiently long distance from the plasma injector, the effect of such inhomogeneities can be reduced to a minimum.

<u>Equipment</u>. Fig. 1 shows the block-diagram of the system. The vacuum chamber is of cylindrical shape and 35 cm in diameter. It is made of stainless steel and is fitted with lithium fluoride windows. A coaxial electrodynamic injector is fixed at one of the faces of the chamber. The magnetic dipole and the probes are introduced from the other end through Wilson sealings. The chamber is placed between the mirrors of a Fabry-Perot interferometer operating on a gas laser emission with $\lambda = 3.39\ \mu$. The collimated laser beam entered the plasma through the lithium fluoride window and was recorded by an InSb-detector with output on the oscillograph. A system of coaxially disposed coils could induce a static magnetic field of up to 3000 oe which was switched on only during the setting up of the equipment [6].

The magnetic dipole is a rectangularly shaped slab copper coil made with 4 x 36 cm dimensions. The coil was so placed in a horizontal plane that the directed plasma velocity vector be perpendicular to its large side. The distance between the coil center and the injector could vary from 70 cm to 1 m.

The plasma from the coaxial electrodynamic injector constitutes two plasmoids with velocities of $3 \cdot 10^7$ and $\sim 8 \cdot 10^6$ cm/sec. At the same time, the concentration of the first plasmoid is 3-4 times lower than that of the second. The electron temperature of the first plasmoid is 10-25 ev. Used in the present work were only the first plasmoids, in which the ionization was almost total. During the concentration in the first plasmoid the switching on of the master longitudinal magnetic field attained $1\text{-}2 \cdot 10^{15}\,\text{cm}^{-3}$; without the master field it was $10^{13}\,\text{cm}^{-3}$. The basic experiments were carried out without master field.

The measurements of the dipole magnetic field distribution and of its variation during interaction with the plasma flux were carried out by means of magnetic probes.

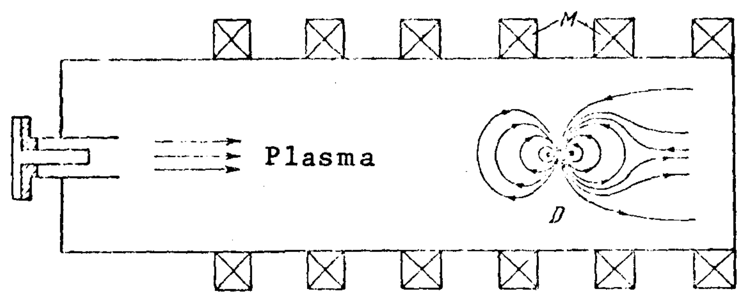

Fig.1

<u>Results of the Experiments</u>. Plasma parameters were so

selected as to ensure that the conditions of the experiments would be as close as possible to conditions in outer space. In particular, the selection of a 10^{13} cm^{-3}, was dictated by such a consideration, although working would have been easier with 10^{14}-10^{15} cm^{-3} concentrations, easily obtainable with the injector used in the present work [2]. The characteristics of the basic conditions of the experiment and the data characterizing the solar wind flow past the geomagnetic field are compiled in Table I.

TABLE I

Indices	Outer Space	Experiment
Temperature	$\sim$ 20 ev	20 ev
Directed plasma velocity	$3-5\cdot10^{7}$ cm/sec	$3\cdot10^{7}$ cm/sec
Mean free path length	10^{13} cm	10^{2} cm
Magnetosphere dimensions	$5\cdot10^{9}$ cm	10 cm
Larmor radius of electrons	$6\cdot10^{4}$ cm	$5\cdot10^{-2}$ cm
Dimensions of inverse field region	10^{9} cm	3-5 cm

The results of magnetic measurements at $n = 5\cdot10^{12}$ cm^{-3} are shown in Fig.2. The dashed curve shows the dipole field in the absence of a plasma flow. The solid curve shows the plasma-distorted field distribution. It may be seen that a virtually total dislodging of the magnetic field by the plasma takes place at distance from the dipole. As was to be expected on the basis of magnetic flux preservation the field increases in the vicinity of the dipole forming a bounded magnetic cavity. The point of intersection of the curves corresponds to the field whose pressure is equal to the pressure of directed flux ρv^2. Near the intersection point of curves the interaction between the plasma and the dipole field results in a change of the direction of the lines of force over a sector of 1-2 cm in length. It is natural to ascribe the occurrence of magnetic field momentum with a sign opposite to that of the dipole field, to the amplification of the magnetic field frozen-in the plasmoid at the shock wave front.

To check our assumption, experiments were carried out with variations in the direction of the dipole magnetic field. The

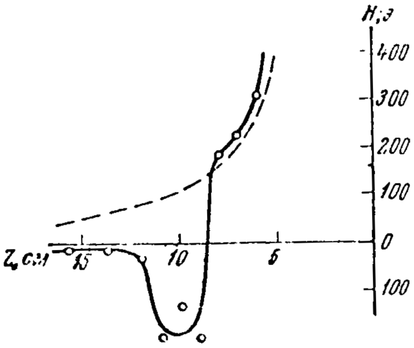

Fig.2

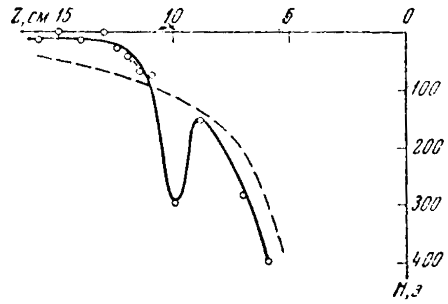

Fig.3

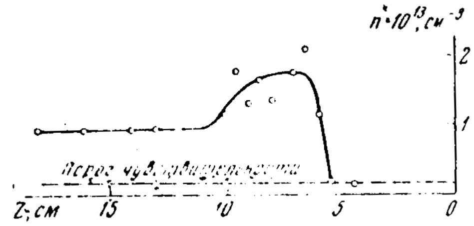

Fig.4a

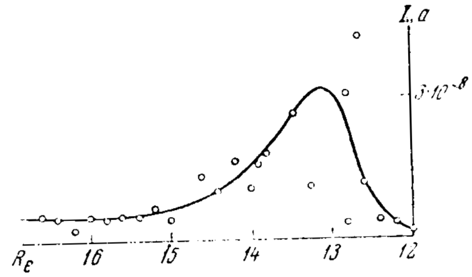

Fig.4b

results of these experiments are shown in Fig.3. The pulse sign remained unchanged with variation in the direction of the dipole lines of force which confirms the assumption of the intensification of the plasmoid field on the wave front. An independent confirmation of this assumption was also in the results of experiments in which the magnetic "wall" was replaced by a hard surface. In this case the direction of the magnetic field momentum and its amplitude remained unchanged (Fig.3). It should be noted that the magnetic field momentum originates at the plasmoid front and is, apparently, due to contraction of the magnetic field frozen-in.the part of the plasmoid whose concentration is lower than the plasma concentration in a settled flow.

The results of direct measurements of plasma concentration also speak in favour of the assumption of shock wave formation during supersonic flow past a magnetic dipole. Fig. 4a shows the distribution of concentration measured with an interferometer operating in the $\lambda = 3.39$ mk wavelength. The region in which an increase by a factor of 1.5-2 takes place in the concentration is of 4-5 cm. dimension. On the basis of the available data it can be asserted that plasma concentration in the magnetic dipole cavity does not exceed 10% of plasma concentration in an unperturbed flow. For the sake of comparison we brought out in Fig.4b the data on concentration measurements on IMP-2 satellite, carried out on October 9, 1964 [5]. The current I in the electron trap, i.e., a quantity proportional to $n\sqrt{T_e}$, is plotted along the ordinate axis.

The oscillograms of the magnetic field (left) and of interference roads (right) are shown in Fig.5 for the most typical cases of the interaction between plasma flow and the dipole field: a) the dipole magnetic field is zero; b) the dipole magnetic field is switched on, Z = 15 cm; c) the dipole magnetic field is switched on, z = 4 cm, the amplification is reduced by a factor of 10; d) the dipole magnetic field has an opposite direction, z = 10 cm; e) the dipole magnetic field is switched off and a hard obstacle is placed at a distance of 0.5 cm from the sensor. The duration of scanning is 70 mk sec.

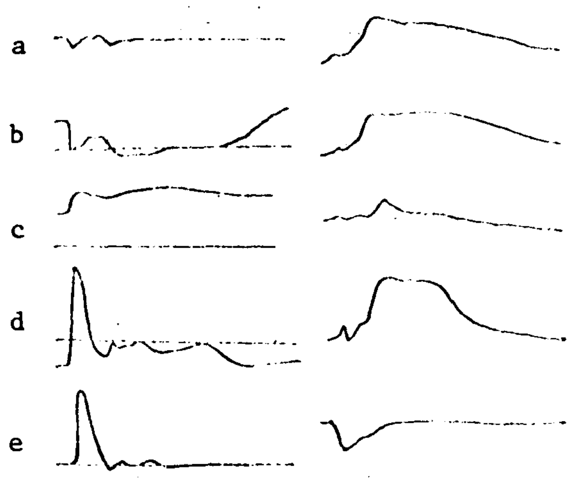

Fig.5

The formation of a shock wave at a 10^{13} cm^{-3} concentration cannot be explained by dissipation due to Coulomb collisions since the length of the free path of ions exceeds considerably the characteristic dimensions of the interaction region between the plasma and the magnetic field. In the investigated experiment, the formation of a shock wave may take place solely at the expense of collisionless processes, among which the ion sound build-up and the two-beam instability must be mentioned in the first place. At the present time it is difficult to make an unambiguous selection between the possible dissipation mechanisms. However, the significant width of the transitional region plasma-magnetic field, as compared to c/ω_0 points also to the presence of such a mechanism.

In conclusion, it should be noted that the pattern of magnetic field distribution during supersonic plasma flow past a two-dimensional dipole agrees in its general traits with the magnetic measurements carried out by means of Earth's artificial satellites. Thus, for instance, according to data obtained on Satellite Explorer-12 [3], the measured field exceeds tha dipole field starting from $7 \cdot R_e$ and up to the boundary of the cavity. In its vicinity a sharp variation by 180° is observed in the field direction. This sharp variation in field direction is often taken as the boundary of the magnetosphere.

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